Developing a Resource Management and Monitoring Protocol for a Semiarid Landscape with Extensive Oil and Gas Development Potential

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by

Randall B. Boone

Natural Resource Ecology Laboratory
Colorado State University
Fort Collins, Colorado

Jason J. Taylor

Bureau of Land Management
National Operations Center
Branch of Assessment and Monitoring
Denver, Colorado

David M. Swift

Natural Resource Ecology Laboratory
Colorado State University
Fort Collins, Colorado

Paul H. Evangelista

Natural Resource Ecology Laboratory
Colorado State University
Fort Collins, Colorado

Ed Hollowed

Bureau of Land Management
White River Field Office
Meeker, Colorado

July 2011

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Contents

Abstract

Energy extraction activities in the Intermountain West doubled from 1990 to 2007. Within the Bureau of Land Management's (BLM's) White River Field Office (WRFO) management area, 95 percent of new oil and gas development activities are anticipated to occur in the Piceance Creek Basin. Oil and gas development activities are leading to changes in the landscapes administered by the BLM. These landscapes provide habitats for many species, including some that are rare, and ecosystem services important to the public, including recreation, grazing, and energy production. WRFO personnel are developing a resource management plan amendment (RMPA) related to oil and gas extraction activities, with a goal to manage for long-term ecological viability, as defined by the Federal Land Policy and Management Act. A timely, cost-effective, scientifically valid, and publicly accepted approach to monitoring the effectiveness of land management decisions and practices was desired as part of the RMPA. To meet this need, the BLM, in collaboration with Colorado State University, and with input from the U.S. Geological Survey, developed this RMPA companion document, which proposes a resource management and monitoring protocol (RMMP). Once all phases are complete, the RMMP will include specific protocols and models for using remote sensing and other geospatial technologies, a series of metrics judged by experts as likely to reflect important changes in landscapes over time, and a means to report the results of the RMMP to the public, to operators, and within the BLM.

Introduction

Energy extraction activities in the Intermountain West doubled from 1990 to 2007 (Naugle et al. 2011). These activities are leading to changes in the landscapes administered by the Bureau of Land Management (BLM). These BLM-managed lands provide habitat for a variety of species, some of which are rare, and *ecosystem services* (see "Glossary" for words in italics) important to the public (MEA 2005). Ecosystem services provided to the public include direct uses, such as energy production, hunting, hiking, livestock and wild horse grazing, and other resource uses of the federal lands, and indirect services, such as snow and water storage and nutrient cycling. Oil and gas development activities may lead to changes that degrade the condition, sustainability, and resilience of BLM lands (Rapport et al. 1998; de Soyza et al. 2000) potentially affecting important ecosystem services. One aspect of BLM's multiple use mandate, as defined by the Federal Land Policy and Management Act (FLPMA), is to achieve "harmonious and coordinated management of the various resources without permanent impairment of the productivity of the land and the quality of the environment . . . ." In part to meet this FLMPA mandate, the White River Field Office (WRFO) of the BLM is developing a resource management plan amendment (RMPA) related to oil and gas development activities. The RMPA will include novel resource-management practices to monitor oil and gas related development and landscape change expected in the WRFO over the next several decades.

To adhere to FLPMA, achieve the BLM vision of balanced stewardship, and ensure that some of the aforementioned uses (i.e., ecosystem services) are not unduly compromised by development of energy reserves or incomplete reclamation, the WRFO recognized the need for a timely, cost-effective, scientifically valid, and publicly accepted monitoring approach to evaluate the effectiveness of the RMPA and resultant oil and gas extraction activities in the area. To meet this need, the BLM, in collaboration with personnel from Colorado State University, and with input from the U.S. Geological Survey (USGS), developed this RMPA companion document. This Technical Note describes a resource management and monitoring protocol (RMMP) relative to oil and gas extraction activities, including the rationale and recommended approach. The RMMP has an intermediate goal of integrating the results of this effort into the BLM planning process and a long-term goal of integrating management aspects beyond oil and gas activities (e.g., grazing effects), but both of those goals are beyond the scope of this document.

From a fundamental perspective, the RMMP is an oil and gas RMPA implementation-monitoring protocol that has two immediate objectives. The first objective is **to determine and describe the most efficient and effective way to inventory, monitor, and report surface *disturbance* and *reclamation* activities**, with the inventorying and monitoring being completed via some combination of geospatial technologies and fieldwork. The second objective is **to develop an assessment protocol, using landscape metrics and results from fieldwork to quantify and understand landscape change related to oil and gas development**, including the effects of surface disturbance and reclamation activities, as well as changes due to other land uses and natural causes. The RMMP will be developed in a two-stage effort. The first phase is referred to as the "ideas" phase, which is described in this document, and proposes a data management system. The second phase is referred to as "implementation" and will include development of detailed processes and models to achieve project objectives and analyses to quantify notable change in metrics. Once both phases are complete, the RMMP will include specific protocols and models for using remote sensing and other geospatial technologies, a series of *metrics* judged by experts as likely to reflect important changes in landscapes over time, and a means to report the results of the RMMP to the public, to operators, and within the BLM. Ultimately, an effective monitoring protocol will allow the WRFO to adopt a more rigorous approach to management. Land managers will be able to identify undesirable trends in a changing landscape and practice *adaptive management*, altering approaches to improve conditions.

The authors acknowledge the tremendous importance of energy extraction as a revenue source for private, local, state, and national interests, and the value of energy to citizens of Colorado and the nation. We also acknowledge the disruption that oil and gas extraction may have on landscapes and residents, and its potential negative effects on *ecosystems*. This document is not intended to sway those involved in political decisions. Instead, we seek to summarize scientific information in an unbiased way, and to suggest measures that will improve the monitoring of selected ecological and physical attributes in areas where oil and gas are being extracted.

Focal Landscape

Public lands in Colorado's Western Slope are undergoing rapid transformations in land use and land cover, largely resulting from extraction of oil and gas resources. This process of land cover change is expected to continue for decades. The WRFO encompasses 2.6 million acres of publicly and privately owned land in northwest Colorado. The region includes the Northern Piceance (or Piceance Creek) Basin, roughly 700,000 acres, which is expected to support over 95 percent of new oil and gas development in the area of concern to the WRFO. The Piceance Creek Basin is a nationally important natural gas reserve, but is also home to large herds of migratory elk (*Cervus canadensis*) and mule deer (*Odocoileus hemionus*), populations of greater sage-grouse (*Centrocercus urophasianus*), threatened plants such as the Dudley Bluffs bladderpod (*Lesquerella congesta*) and Dudley Bluffs twinpod (*Physaria obcordata*), significant cultural and paleontological resources, and a wild horse herd management area, and it is grazed by livestock and used by people for outdoor recreation.

The landscapes throughout the majority of the BLM-managed portions of the WRFO are part of the Colorado Plateaus Ecoregion. Almost 50 million years ago, the region was covered by Lake Uinta, similar in size to modern-day Lake Michigan. Organic matter accumulated in the lake and formed oil shale, natural gas, and other energy resources that are now of great interest. Today the region is semiarid. In Meeker, Colorado, the average temperature in January ranges from 7-37 °F, and in July, from 47-86 °F (BLM 2006). Precipitation (as rain and snow) is well distributed throughout the year with annual totals of between 12 and 20 inches (CDOW and USFWS, undated). Some precipitation events can be intense, causing flooding and erosion. Soils are diverse, and the topography is complex. Vegetation composition has been relatively stable, comprising sagebrush (*Artemisia* spp.), shrublands and grasslands, Colorado pinyon pine (*Pinus edulis*), and Utah juniper (*Juniperus osteosperma*) communities, with deciduous forests along the riparian areas and midslopes of mountains and conifer forests at higher elevations. Livestock grazing has been a dominant land use in the area. Invasion of the region by exotic plant species, especially cheatgrass (*Bromus tectorum*), and increased representation of introduced grazing-tolerant grasses, such as Kentucky bluegrass (*Poa pratensis*), have modified the ecology of the system, reduced its capacity to support herbivores, and compromised other ecological functions.

Potential Effects of Oil and Gas Extraction and Other Activities on Ecosystem Services

Potential effects of oil and gas extraction on ecosystem attributes that provide services are varied, and include changes to soils, water, vegetation, wildlife, and the atmosphere. Other activities, such as livestock grazing, off-road vehicle recreation, and mining also alter ecosystem attributes. Some changes are relatively long-term, such as broad-scale erosion or projected climate change. Other changes are short-term, such as year-to-year changes in wildlife populations or weekly changes in air quality. The RMMP will highlight changes in selected ecosystem attributes that occur in the short-term, as well as quantify long-term changes in ecosystem attributes. For example, short-term changes include the amount of bare ground, traffic, fugitive (i.e., airborne) dust, and point-source pollution. Long-term changes include, for example, loss of soil crusts, erosion, land cover conversion, changes in stream temperatures, and invasion of nonnative plant species.

Across the western United States, the quantity of sagebrush habitat has been declining for 50 years (Connelly et al. 2000). Sagebrush decline is also occurring in the WRFO, where several sagebrush-obligate species occur, such as the greater sage-grouse (*Centrocercus urophasianus)*, Brewer's sparrow (*Spizella breweri)*, and sagebrush vole (*Lemmiscus curtatus*). Populations of deer, elk, and other animals may decline if development-related activities, such as traffic, cause behavioral changes reducing the likelihood that animals will use forage and cover resources near roads. Oil and gas development activities may also alter the behavior of livestock as well, and livestock grazing is another important use of landscapes managed by the WRFO. Lastly, fugitive dust from oil and gas extraction activities can decrease air quality and coat nearby vegetation, including threatened and endangered species, reducing their productivity and possibly affecting their long-term existence.

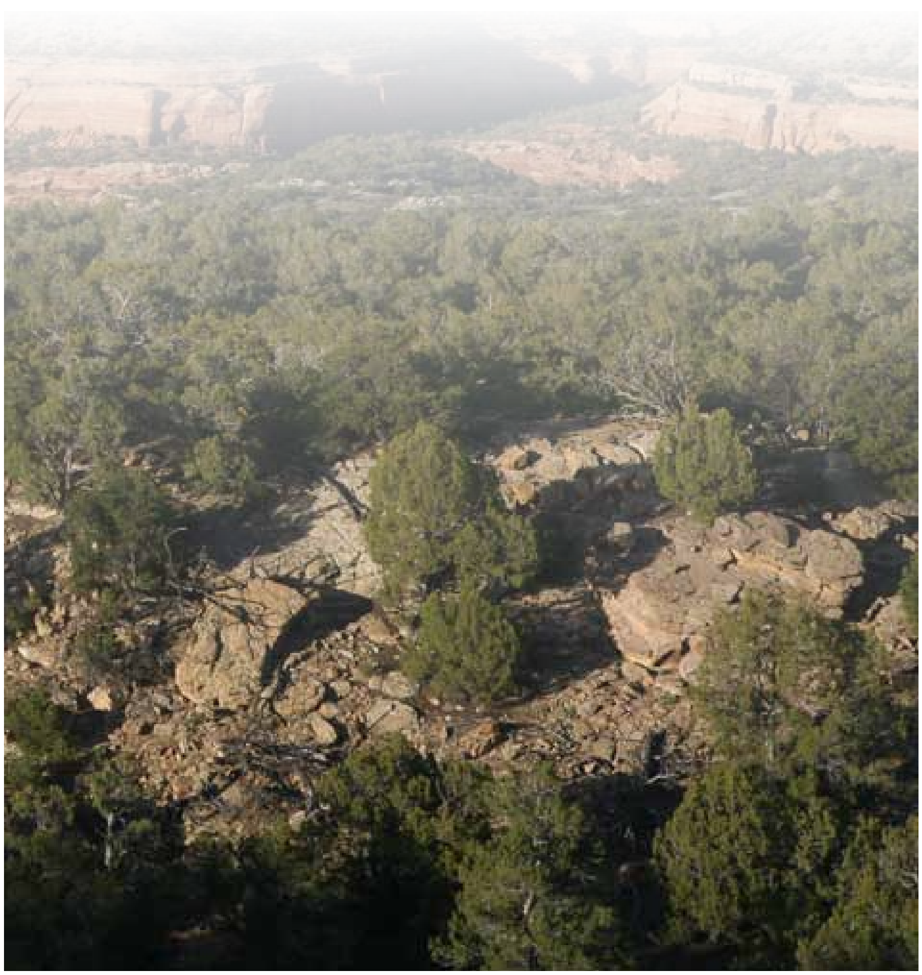
Approach to Monitoring Oil and Gas Extraction Activities and Associated Landscape Change

An approach to monitoring proposed oil and gas extraction activities, reclamation, and the infrastructure that supports these activities could be relatively straightforward because of reporting requirements placed upon lease holders. To drill on public lands where energy companies have leased mineral rights from the BLM, companies must submit the proposed well locations, plans for access roads, and other details to the BLM for review. As plans are approved and drilling and oil and gas extraction commences, the BLM requires updated reports from the companies. Lastly, as well pads, roads, and pipeline paths are revegetated, the BLM is informed of the state of reclamation. Schematics collected via these reporting requirements could serve as a basis for tracking development activities with a sample of the information checked for accuracy and consistency by the BLM using either high *spatial resolution* imagery or field visits.

In addition to oil and gas reporting assessments, remote sensing and other geospatial technologies will provide the foundation for mapping and monitoring related landscape changes. Multiple imagery sources (at different spatial, spectral, and temporal resolutions) including NAIP (National Agriculture Imagery Program), QuickBird, and RapidEye will be employed in concert to address management questions. Staff from BLM's National Operations Center (NOC), have been working in conjunction with the WRFO to develop a protocol for disturbance and reclamation mapping based on the aforementioned imagery. The protocol includes: field sampling for remote sensing imagery development and *classification accuracy* assessments; development of a percent-cover data stack (including percent bare ground, percent litter, percent herbaceous, percent shrub by species, and percent tree by species); a discrete-class land-cover map; and a change-detection model based on comparisons of these data products through time. This combination of efforts will allow for baseline disturbance and vegetation to be mapped, and monitored. The validation of future site-level disturbances will provide a utility for tracking reclamation, coordinating reclamation-compliance field activities, and calculating many of the landscape measures (e.g., habitat totals, habitat isolation, etc.) that will be integral to the RMMP. While these efforts are largely underway, the second phase of the RMMP will fully evaluate and explain how current remote sensing efforts will be employed in the RMMP. Furthermore, processes and models will be detailed as to how remote sensing and geographic information systems (GIS) will be used for disturbance and reclamation mapping to calculate each of the landscape measures of interest.

Although acquiring information on development activities (via leaseholder reporting requirements and remote sensing) could be relatively straightforward, managing and visualizing that information is not. To aid in visualization and reporting (for the BLM, leaseholders, and the public, simultaneously) the USGS Fort Collins Science Center has created a data management system that has proven useful in tracking and reporting oil and gas development activities in Wyoming. This web-based system, originally called the Jonah Infill Data Management System, allows managers to map the state of well pads across an energy field, and to perform complex queries to extract required reporting information. Changes in oil and gas development activities may be mapped through space and time using the system.

The web- and GIS-based data management system (DMS) is being adapted by the USGS to apply to WRFO-managed lands. This application is a foundational component of the RMMP. The DMS will allow surface disturbance, reclamation, and other oil and gas extraction activities to be planned and potential effects to be previewed, with both activities and potential effects to be expediently tracked and reported, which meets several parts of the first objective of the RMMP. The DMS will be helpful with the second objective of the RMMP as well. The landscape and population attributes to be monitored under the RMMP include information gathered through space and time, and can be visualized and reported in the DMS. The DMS should include visual indicators summarizing the degree of change in the landscape attributes or measures. For example, the indicator may be a graphical element that is "green" when change from one period to the next is small, "yellow" when the change is moderate, and "red" when the change is large. Most of the proposed metrics have a strong spatial component, and the same color codes may be used to show, for example, areas of small (green), moderate (yellow), or large (red) changes in vegetation cover. Green, yellow and red indicators designed to show varying levels of change in traffic or pollution would also be useful. The suite of comparisons incorporated into the RMMP may be summarized on a single page in the DMS.



Approach to Defining Change

Defining what may be considered notable changes in ecosystems is contentious. Sustainability science is a new discipline and much remains unknown (Parrish et al. 2003; Rindfuss et al. 2004). Specifically, changes in ecosystem attributes that are sufficient to destabilize an ecosystem, or threaten sustainability, are mostly unknown. Ecosystem responses may be nonlinear and with unknown thresholds, meaning that very rapid changes may occur with little warning. Progress in sustainability science is being made (e.g., Clark et al. 2001) and scientists have had some success in determining the causes of past collapses, but quantifying thresholds of change that will cause future collapses remains difficult for all but the simplest ecosystems, and the degree to which thresholds from one system inform others is poorly known.

A further consideration is the frequent difference between changes that threaten the long-term functioning of the ecosystem and changes that might be unacceptable to the public. Consider the hundreds of plant and animal species that occur in the lands managed by WRFO. If some species of concern to the public were extirpated, the ecosystem in which they occurred is likely to remain stable; there are many examples where species have gone extinct and the ecosystems in which they had occurred continued to maintain stable function (reviewed in McCann 2000). Nonetheless, the outcome may not be acceptable to the public.

Difficulty in defining change, and the public perception of change, is addressed in three ways. First, the focus will be on change that reflects both long-term sustainability and ecosystem attributes describing services provided to humans. Second, any thresholds used or derived in the RMMP do not advocate management action by the BLM or have regulatory authority. Lastly, just as landscapes can be adaptively managed, the RMMP itself will be subject to adaptive modifications. For example, under an *adaptive management* model, metrics may be added or modified as new insights are gained, while protecting the integrity of the data that allows comparisons through time (Kotliar et al. 2008).

The RMMP will quantify selected landscape changes specifically related to disturbances by oil and gas extraction activities and will not specifically address changes due to other land uses, such as livestock grazing and recreational use, and regional or global-scale events, such as changes in climate associated with increased concentrations of greenhouse gases. The role of the RMMP is to determine methods to highlight notable change and to report those changes within the DMS graphical user interface and databases. As changes are indicated, managers can use the DMS, plus other resources, to explore underlying causes and adapt management as appropriate. Conceptual diagrams linking human land use and other stressors to environmental change (such as those in Miller 2005) may be referenced by researchers and land managers to understand relationships between observed landscape changes and potential outcomes. For example, an analyst may recognize an area showing large changes in vegetative cover as having the footprint of a recent wildland fire or a broad-scale decline in vegetation cover during a time of drought. But other changes may require more intensive review. Landscapes within the WRFO that have experienced relatively little disturbance may be delineated and used as "baseline" or "control" areas. Managers can compare changes in areas of interest with changes noted in these areas, to see if they are likely associated with disturbance, or if the changes are seen regardless of disturbance. Lastly, managers can compare notable changes with long-term landscape dynamics. For example, managers expect vegetation cover to decline in drought, but if the severity of drought and decline in vegetation cover had been related in past analyses, the current change could be compared to the long-term changes to see if it was more or less extreme.

Where possible, change thresholds will be defined based on their *historical range of variation* (Landres et al. 1999). Most landscape attributes continually vary. For example, vegetation cover is sensitive to the amount and timing of precipitation in a given year. Change alone is insufficient to be highlighted as a concern in the DMS—change is ubiquitous. In one aspect, the RMMP seeks to highlight changes in vegetation cover that are "relatively large." To define what relatively large may be, typical changes in vegetation production over years must be quantified. Historical ranges of variation will be calculated based on satellite imagery where imagery is available over a sufficiently long period, and for changes in wildlife populations, where long-term surveys have been conducted. Standard deviations in responses, and changes that exceed a multiplier of the standard deviation, may be identified. Numerous concerns, idiosyncratic to each type of change, must be addressed when judging historic variability, but some satellite data are available back to the 1970s, for example, and aerial photographs are available for decades prior, and together they may provide ample data for determining historical variation for some kinds of change.

For some types of change, a historical range of variability approach is inappropriate. For example, oil and gas development in the lands managed by WRFO has been progressing at unprecedented rates. For development-based change measures, future landscape change will be simulated and thresholds quantified based on the degree of change judged by experts to be of interest to landscape managers. Two degrees of notable change may be used, such as a change from year to year greater than a given amount (e.g., 3 percent) and change across any number of years of some larger value (e.g., 6 percent). With that, yearly changes that were below the lower threshold would still raise flags suggesting notable change across several years.

Analyses to identify reasonable thresholds for the measures of change to be adopted will be done in the second phase of the RMMP development. Issues regarding sampling design, including spatial and temporal needs, will also be explored. Either through analyses of historical ranges of variation or expert assessment about rates of change through time, acceptable ranges of variation (Parrish et al. 2003) will be defined, and responses that exceed those ranges will raise alerts in the RMMP. Based on new information, or a better understanding of related systems, threshold values may be changed at a later date. Also, ecosystems experience gradual change irrespective of anthropomorphic stressors (Miller 2005), and after careful review, managers may shift the central value around which ranges of variation are defined. Although more cautious users may choose to adopt different thresholds that signal concern, the RMMP will report quantifiable levels of change using the process described, which should help make monitoring more consistent.

Approach to Identifying Metrics to Monitor

Conceptual Diagram

The landscapes managed by the BLM WRFO are working landscapes. They provide important services, ecosystem-based (including wildlife habitat) and otherwise, to residents of the area, visitors from outside, and users of energy throughout the country. It is important that oil and gas extraction proceeds in the area, but it is also important that the ability of the landscapes to provide other key ecosystem services is not unduly degraded. As part of the monitoring process, the BLM intends to track metrics describing ecosystem attributes that either directly or indirectly reflect the ability of the system to provide those ecosystem services. For example, attributes related to direct effects include bare ground and fragmentation, while attributes related to indirect effects include vegetation and animal population responses. Metrics will be one of several types: landscape spatial-pattern metrics derived from remote imagery; direct measures (i.e., counts) of vegetative variables or species abundance; or general descriptive or spatial statistics used to describe abundances.

Figure 1 is a conceptual diagram adapted from Miller (2005) and Kotliar et al. (2008) that

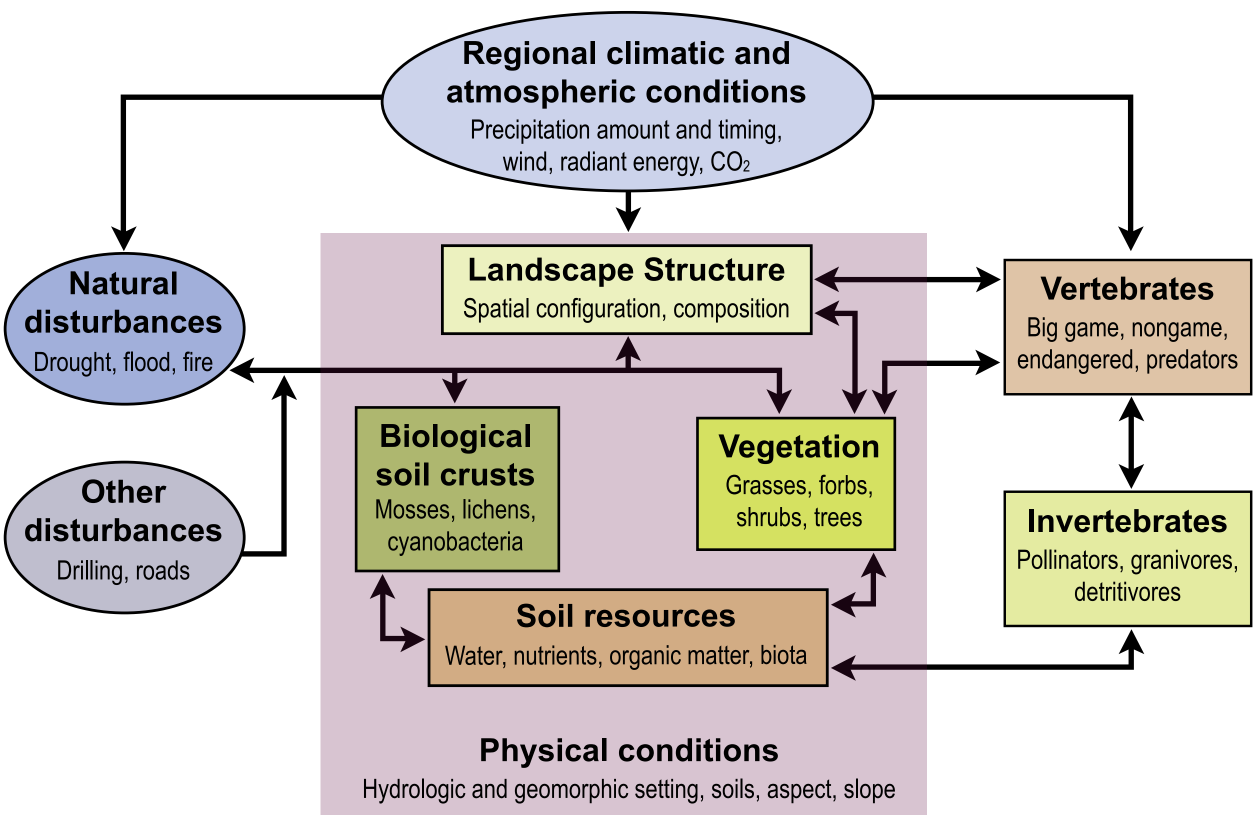


Figure 1. A conceptual diagram illustrating key structural components (rectangles) and drivers of change (ovals) on lands managed by the BLM WRFO. Functional relationships are indicated by arrows. Example components or relationships are shown in a smaller font (adapted from Kotliar et al. 2008 and Miller 2005). "Other disturbances" refer to those that are anthropogenic, including oil and gas extraction and livestock grazing. "Vertebrates" refer to wild animals.

encapsulates key ecosystems components and relationships that describe or influence mesolevel ecological structure or function and that helps identify metrics to monitor. Regional climatic conditions influence almost all components of the ecosystem. For example, the amount and timing of precipitation, combined with the physical conditions of landscapes, are important in defining site potential. Disturbances may be natural (e.g., fire, drought, or flood) or *anthropogenic* (e.g., oil and gas development activities, roads, or grazing), either of which may alter vegetation, soil crusts, and landscape structure. Soil resources support vegetation growth and the persistence of soil crusts. In turn, vegetation and crusts promote soil stability and contribute to soil resources through additions of organic matter. Landscape structure is primarily determined by the physical conditions and site potential of an area plus the vegetation, which is itself influenced by landscape structure. Vertebrates and invertebrates influence, and are influenced by, the landscapes they inhabit, including soils and soil resources, vegetation, and landscape structure. Effects of seasonality and severe weather events on vertebrates complete this sketch of the most important components and functions of these ecosystems.

Although all the attributes in the conceptual diagram are considered important, financial and staff limitations within the field office dictate that a parsimonious, meaningful, and achievable suite of metrics be selected to describe key ecosystem attributes that are tied to essential ecosystem benefits. Attributes that fit well with ongoing efforts by the BLM and other organizations were also sought.

Theoretical Rationale

The simplicity of the conceptual diagram (figure 1) masks the innumerable components and relationships that exist in the focal ecosystem. For instance, typical small riparian plots that include 50 plant species and dozens of bird species occur in the project area (e.g., Baker 1990; Kingery 1998). To identify a manageable suite of metrics for monitoring, logic analogous to an approach now common in conservation planning, the coarse-filter approach was used. In the 1980s, The Nature Conservancy adopted the coarse—filter/fine-filter approach to conserving communities, which was later expanded to include patterns of physical distribution and disturbance (Noss 1987; Hunter et al. 1988). The coarse-filter approach was a response to the species-centric conservation efforts of the 1970s. In conserving biological diversity, the coarse-filter approach protects representative communities, such that the vast majority of species are conserved. For any species not conserved by the coarse filter, specific measures of conservation are adopted—the fine filter component of the approach. A related idea is that of umbrella species (reviewed in Roberge and Angelstam 2004), where the conservation of a species with broad-ranging requirements may help conserve many other species. Classic examples of umbrella species are large carnivores, which require large areas of relatively undisturbed areas. By putting in place conservation-network designs so that large carnivores persist, species with less expansive requirements—the species under the umbrella—will be conserved. A plan to conserve biodiversity is outside the scope of the RMMP, but the logic of using a limited number of well-chosen metrics to measure change in important ecosystem attributes applies here. For example, recognizing that the greater sage-grouse is a species of management concern in the lands managed by the WRFO, metrics may be proposed that reflect changes in the vegetation sage-grouse use most often—sagebrush. Monitoring changes in the sagebrush vegetation type can serve as an umbrella for habitat used by a suite of other sagebrush obligate species, such as the sagebrush vole and Brewer's sparrow.

In considering what metrics to select through the filter approach, one aspect of note is that metrics used to reflect landscape structure are often highly correlated (Cushman et al. 2008). For example, the mean size of habitat patches and patch density (common landscape metrics) are redundant because they represent the same information (McGarigal et al. 2002) measured from different perspectives; measuring one or the other is reasonable, but measuring both is typically unnecessary. Rarely is the question about the relatedness of potential metrics as clear cut as in this size/density example, but it reasonable to expect that other attributes may be related. For example, measuring a select number of air pollutants produced during oil and gas extraction activities would presumably reflect concentrations of other pollutants known to co-occur.

Practical Considerations and Steps Taken

Expert input, information from the literature, workshop discussions, a field visit, and peer review were used to create and refine this ideas proposed in this document. In September 2009, a group of 22 experts in a diversity of domains (e.g., landscape, big game, and avian ecologists and air quality, riparian, and spatial analysis experts) gathered for a 1-day workshop at Colorado State University in Fort Collins (see table 1 for a full list of participants). Participants were provided background information on issues of concern in the Piceance Creek Basin. Speakers were then asked to review potential monitoring metrics for attributes within their area of expertise (e.g., mule deer, sage-grouse, air quality, acoustics, and disturbance). The workshop concluded with a lengthy freeform discussion. Core CSU team members (Swift, Boone, Evangelista) then made a site visit to the Piceance Basin in November 2009, hosted by the WRFO staff. The group toured a variety of lands disturbed by oil and gas

Table 1. Participants in a workshop September 23, 2009, at Colorado State University, Fort Collins, where attributes of a monitoring protocol for western Colorado lands were discussed.

Participant	Affiliation
Chuck Anderson	Colorado Division of Wildlife
Matt Bobo	Bureau of Land Management
Randall Boone	Colorado State University
Tasha Carr	U.S. Geological Survey
Paul Evangelista	Colorado State University
Maria Fernández-Giménez	Colorado State University
Ed Hollowed	Bureau of Land Management
Danielle Johnston	Colorado Division of Wildlife
Kim Kaal	Colorado Division of Wildlife
Megan Kram	The Nature Conservancy
David Mack	U.S. Geological Survey
Al Maki	Exxon Mobil Corporation
Jana Milford	University of Colorado
Terri Schulz	The Nature Conservancy
Dave Swift	Colorado State University
Jason Taylor	Bureau of Land Management
Janice Thomson	Wilderness Society
Gordon Toevs	Bureau of Land Management
Brett Walker	Colorado Division of Wildlife
Kent Walter	Bureau of Land Management
Christine Wiedinmyer	University of Colorado
Ken Wilson	Colorado State University

development, where activities were at different stages. The information gathered during these activities influenced the content of the RMMP, in terms of general direction, specific metrics to be monitored, and metrics that were not incorporated. For example, the CSU team had planned to incorporate suggestions for acoustic monitoring into the RMMP, but after witnessing the relatively low noise levels associated with modern oil and gas development activities, the team determined that limited resources would be better used for monitoring other ecosystem attributes. Also, the team learned that sources of permanent noise are localized, most noise is transitory, monitoring acoustics in the area is not practical, and lastly, linking changes in noise to ecological effects is difficult. That said, further research into acoustic effects on animal behavior is suggested.

The RMMP approach intends to integrate with, and take advantage of, an existing constellation of BLM national agendas, standards, and ongoing fieldwork within the WRFO (e.g., long-term vegetative trend monitoring) and other related activities, both current and past. For example, assessment, inventory, and monitoring (AIM) and rapid ecoregional assessments (REAs) are two national-level BLM initiatives that were considered in the RMMP design. The AIM Strategy describes indicators and methods for monitoring landscape changes at multiple scales and for improving coordinated quantitative monitoring for detecting changes in land health. Efforts to define terrestrial indicators for the AIM Strategy were described by Herrick and others (2010). A thorough review of this effort was done as the RMMP was designed to find the points of convergence between national and local needs and to promote both efforts simultaneously. The REAs intend to identify landscape-scale, ecologically based conservation and restoration needs for developing future resource management and use objectives. The RMMP is considered, at least partially, an implementation/monitoring mechanism for REA-like results. Because the RMMP will be completed prior to when the Colorado Plateaus REA is completed, the authors recognize the need for the RMMP to remain flexible to adapt to REA results as they become available. The standards for public land health (e.g., Pellant et al. 2005) guide aspects of stewardship on BLM lands as well as resource management planning in Colorado. Although the RMMP may be more inclusive or broader in scale, it should not be in conflict with the standards, but rather, where applicable, should harness fieldwork already being completed to assess public land health and long-term vegetation trends. Other pertinent efforts are either currently ongoing or are recently completed. The Nature Conservancy is working through a conservation action plan (CAP) for the White River watershed,

the Wilderness Society has recently completed a fragmentation mapping study (Wilbert et al. 2008), and the USGS designed a regional approach to monitoring related to wildlife and energy development (Kotliar et al. 2008). Each of these efforts was reviewed prior to completing the first phase of the RMMP in an effort to learn from and take advantage of the work.

During metric selection, priority was given to metrics that are: (1) ecologically or socially relevant and illuminate changes of interest to BLM WRFO land managers, especially related to implementation of the RMPA; (2) demonstrated in the literature to be effective and have the potential for being successfully and reliably calculated over the long-term, considering both technical and financial limitations; (3) interpretable to the extent that decisionmakers and the general public can understand the meaning of changes in the metrics; and, (4) built upon data currently being collected, such as long-term vegetative trend monitoring . In some cases, new field data will need to be collected to monitor specific landscape attributes. An attempt was made to ensure that any newly suggested field-collection efforts could be tiered to the existing, seasonal field campaign. In addition, metrics that use remotely sensed data to provide local-to-regional views of change and that are calculated based on the geometry of landscapes were favored. Continuous variables were favored over those that yield categories of change, as they are more flexible when merged into larger monitoring efforts and more helpful as coarse filters. Lastly, whereas some monitoring plans call for modeling from which cumulative effects of changes on landscape attributes or animal populations can be inferred, metrics representing observable changes on the landscape were sought for the RMMP. That is, rather than combining the effects of several landscape changes into a synthetic metric (e.g., what would be a dependent variable in such a model, such as "sage-grouse habitat"), the RMMP seeks to monitor the changes that would be input into such syntheses (e.g., sagebrush cover and disturbance).

Proposed Metrics

The proposed metrics are summarized in table 2. It is a minimal set of metrics, such that key attributes of each of the main resources or effects related to important ecosystem services are monitored. Figure 2 provides an iconic interpretation of the ecosystem resources or effects captured in the conceptual diagram (figure 1). For each metric, the following information is included: the name of the metric and its units ("Indicator"); the general ecosystem attribute the metric is meant to address ("Use") with its corresponding number in figure 2; the

Table 2. Summary of resource-monitoring metrics proposed to be incorporated into the RMMP. The metrics are sorted from those considered most important or readily available, to those least pressing, most challenging to monitor, or already monitored by other organizations and referenced in the RMMP. "Geospatial" includes spatial analyses in a GIS and analyses of remotely sensed images.

Resource or Effect	Proposed metric	Primary sources	Significance
Soil	Bare ground	Geospatial	Excessive exposed soil may indicate poor range conditions, erosion potential, overgrazing, or disturbance.
Vegetation	Sagebrush cover	Geospatial	Declines in sagebrush land cover may highlight risks to species that depend upon that land cover type. Old-growth pinyon-juniper is an uncommon cover type important for some species and of conservation interest in its own right. More generally, changes in vegetation composition may indicate long-term changes in environmental conditions, use, and range condition.
	Old-growth pinion-juniper	Field/ Geospatial	
	Composition	Field	
Surface Disturbance	Road density	Geospatial	Species of special concern in the area (e.g., sage grouse, mule deer) as well as others avoid areas of disturbance. Recreational users select less disturbed areas as well. More generally and collectively, these indicators reflect the direct ecological footprint of oil and gas extraction activities in the region.
	Well-pad density	Geospatial	
	Distance to roads and wells	Geospatial	
	Pipeline density	Geospatial	
	Area disturbed/section	Geospatial	
	Total area disturbed	Geospatial	
	Area reclaimed/section	Geospatial	
	Total area reclaimed	Geospatial	
	Well-pad status	Reports/Field	
	Road traffic	Field	
Atmospheric	Particulate matter	Field	Excessive levels of particulates or ground-level ozone can damage plants, reduce productivity, harm wildlife, and be a danger to human health.
	Ground-level Ozone	Field	
Landscape spatial pattern	Shape complexity	Geospatial	Wildlife species are sensitive to the amount of habitat available, but also to its spatial pattern. Some species favor edges, some the interior of habitat patches. Some species are migratory, and require suitable habitat along their migratory pathways. Collectively, these landscape spatial pattern metrics quantitatively describe patterns relevant to wildlife.
	Edge contrast	Geospatial	
	Core area	Geospatial	
	Large patch dominance	Geospatial	
	Like adjacencies	Geospatial	
	Nearest neighbor distance	Geospatial	
	Patch isolation Connectance	Geospatial	

Table 2. (continued) Summary of resource-monitoring metrics proposed to be incorporated into the RMMP. The metrics are sorted from those considered most important or readily available, to those least pressing, most challenging to monitor, or already monitored by other organizations and referenced in the RMMP. "Geospatial" includes spatial analyses in a GIS and analyses of remotely sensed images.

Resource or Effect	Proposed metric	Primary sources	Significance
Vegetation	Invasive plants species	Field	Invasive plant species, including exotic weeds, displace native vegetation, and are often unpalatable to wild and domestic grazing animals. Tracking changes in their abundance influences management practices, including control of early invasions.
Water Quality	Dissolved solids	Field	Water quality is an integrative measure of conditions within watersheds. Changes in water quality have affects on aquatic ecosystems and may affect wildlife, but also may indicate problems associated with oil and gas extraction.
	Dissolved oxygen	Field	
	Metals concentration	Field	
	Suspended sediments	Field	
Focal species	Mule deer fawn:doe ratio	Field	Mule deer provide recreational opportunities to hunters and wildlife viewers. Sage-grouse and song birds are of conservation concern; declines in their populations may alter management practices.
	Sage-grouse lek counts	Field	
	Song bird abundances	Field	
Soil	Biological soil crusts	Field	Biologically important in stabilizing soils, etc., but unlikely to be disturbed on a broad scale by oil and gas extraction.

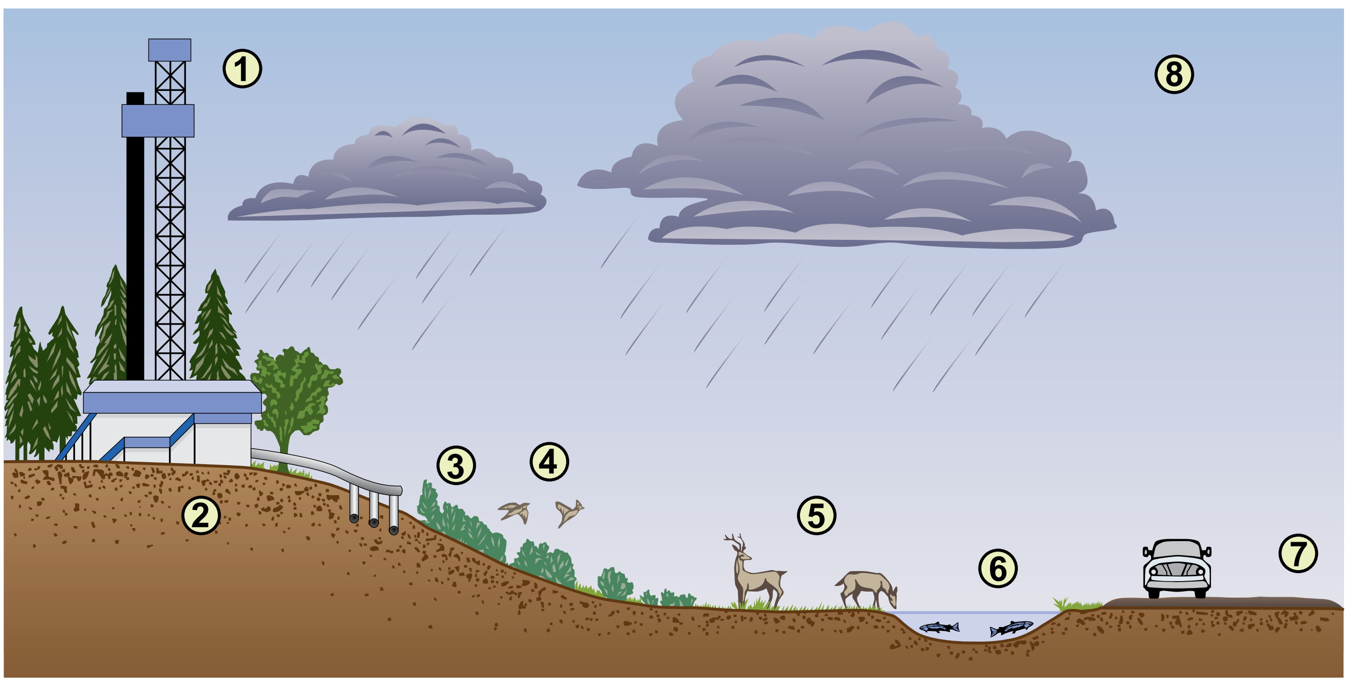


Figure 2. Ecosystem resources or effects of interest include: 1) disturbance, such as from oil and gas development or natural disturbances like fire, 2) soil resources, 3) vegetation, including invasive plants, 4) species of special concern, such as sage grouse, 5) wildlife, such as mule deer and livestock, 6) water resources, 7) landscape structure, and 8) atmospheric resources.

"Spatial scale" over which individual values will be reported (e.g., a section, road corridor, or cell in a satellite image); the "Temporal scale" of the metric, indicating how often new values will be generated or stored; a description of why the metric is important to include in the RMMP

("Justification"); the data that may be used to create the metric and its source ("Potential basis"); any "Field data" required to calculate the proposed metric; and, "Alternatives" considered in place of the metric.

The proposed metrics are agreed upon by experts to be useful; however, they are subject to change or modification. The RMMP will follow an adaptive monitoring approach, and as more information becomes available, changes may be made if appropriate. As technology advances, or as BLM mandates change, the RMMP will be modified to capture new goals. Such modifications will be done with an eye toward keeping temporal comparisons valid. Also, the proposed metrics reflect what can be adequately measured at this time and should not limit future research initiatives. For example, the RMMP does not incorporate a metric for small mammal biodiversity because of the difficulty in quantifying changes in populations of less common species. Regardless of this difficulty, research to improve small mammal monitoring remains important to the BLM. Also, the effects of lights used to illuminate drilling sites at night may have important implications and deserve more research.

The metrics are sorted from those considered most important or readily available, to those least pressing, most challenging to monitor, or already monitored by other organizations and referenced in the RMMP. The metrics proposed for inclusion in the RMMP are:

Indicator: **Bare ground** (percent)

Use: To characterize the broad state of soil stability (2 in figure 2)

Spatial scale: 30-m resolution or finer

Temporal scale: Repeated annually, characterized in the second quarter of the year

Justification: The quantity of bare ground in a landscape is an important *ecosystem health* indicator (de Soyza et al. 2000; Pyke et al. 2002; Pellant et al. 2005). Ground cover such as green or standing dead vegetation, litter, mosses, and lichens are important components of functioning western Colorado ecosystems, and the soil exposed in their absence is classed as bare ground. Vegetation provides forage and cover for wildlife and livestock, secures soils to reduce erosion, helps slow snow drift and runoff to replenish groundwater, and provides aesthetic and economic value to humans. In contrast, bare ground exposes soils to erosion from wind and water and provides habitat for relatively few wildlife species. The percent of bare ground may be increased directly due to human activities, such as road and pipeline construction for oil and gas exploration or expansion of urban areas, or indirectly, such as through loss of vegetation resulting from fine dust settling on leaves. Increases in livestock grazing or decreases in their movements across landscapes may lead to increased offtake of forage in an area and increased bare ground. Lastly, changes in hydrologic cycles may reduce vegetative cover, and increase bare ground. The amount of bare ground is a reliable indicator of rangeland condition that has been used extensively (NRC 1994; Whiteford et al. 1998; Booth and Tueller 2003; O'Brien et al. 2003).

Potential basis: The percent of bare ground has been successfully quantified using remotely sensed images (Booth and Tueller 2003; Washington-Allen et al. 2006). Imagery-based percent of bare ground calculations are regularly produced at coarse resolutions for the globe (500-m-square cells) (Hansen et al. 2004). Those data include significant mixing within the large raster cells, in that a cell may contain a mix of vegetation, bare ground, structures, etc. Images with finer resolution (between 5-m- and 30-m-square pixels) reduce this difficulty, although for this and other reasons, identifying the percent of bare ground in western rangelands remains nontrivial. Classification accuracy is also linked to the amount of bare ground in an area. For areas with more than 50 percent bare ground, classification accuracies can exceed 80 percent, but for areas with much less bare ground, accuracies decrease (Weber et al. 2009). The WRFO is using 5-m-resolution RapidEye imagery in ongoing efforts to map land cover, including bare ground.

Field data: BLM personnel conduct qualitative field surveys through their areas of interest (e.g., Pellant et al. 2005) and long-term quantitative surveys. These surveys include estimates of the percent of bare ground and may be used, in part, as assessment information. A statistically valid sampling schema for quantitative measurement of bare ground across the basin may be required to accurately map this layer. Such a schema is currently being considered at national levels within the BLM.

Alternatives: Percent of vegetative cover is an alternative to percent of bare ground. For natural areas, the two are easily converted (percent vegetative cover = 100 – percent of bare ground). However, for areas with structures or other nonvegetative land cover, that conversion is not appropriate. Given the common use of the percent of bare ground as a metric of rangeland health, it is preferred here.

Indicator: **Sagebrush cover** (percent)

Use: To characterize big game winter forage base, successional status, and the quantity of habitat for a species of concern (3 and 4 in figure 2)

Spatial scale: 30-m resolution or finer

Temporal scale: Repeated annually

Justification: Sagebrush as a habitat supports several species of management interest, including, for example, mule deer, sage-grouse, Brewer's sparrow, and sagebrush vole. Of particular management interest are sage-grouse, which use a variety of habitats, but those most critical to their yearlong survival are expanses of big sagebrush (*Artemisia tridentata*). Sagebrush provides cover for nesting birds, and forbs in sagebrush understories are used by hens and their broods to provide sufficient nutrients early in life (Barnett and Crawford 1994). Sage-grouse most often nest under sagebrush and those that do are more successful than sage-grouse that nest under other plant species (Connelly et al. 1991). Moreover, sagebrush leaves are the primary diet for the birds in winter and an important dietary component in other months (Wallestad et al. 1975). If sagebrush habitats are eliminated through activities or events such as energy development, including roads, pads, and pipelines, large-scale fires, overgrazing, herbicide application, or invasion by annual grasses (e.g., cheatgrass), the areas are no longer suitable for sage-grouse (Beck and Mitchell 2000; Leonard et al. 2000). In summary, the relationship between sage-grouse and sagebrush is so close that the birds are classified as sagebrush obligates (Connelly et al. 2000).

Sage-grouse respond favorably to increasing sagebrush cover only up to a point. The birds select areas with moderate cover (15-35 percent); in areas with more cover, understory plants may be shaded out, and the area becomes progressively less suitable for sage-grouse (Connelly et al. 2000). Also, the leks where males display to attract females are in more open places, surrounded by sagebrush. Sage-grouse biology suggests that the spatial connectedness of habitat patches is less critical than the quantity of habitat; some birds will migrate 75 km or more to reach suitable habitat (Leonard et al. 2000). However, sage-grouse show high fidelity to nesting locations (Fischer et al. 1993), so broad-scale sagebrush conversion or reconfiguration may alter nesting success.

Potential basis: Sagebrush cover has been characterized using remotely sensed data (Knick et al. 1997; Sivanpillai et al. 2009). There are ongoing efforts within the WRFO using 5-m-resolution RapidEye imagery to map land cover, including sagebrush cover. More advanced datasets may aid in mapping sagebrush cover and canopy height, such as hyperspectral data and LiDAR remote sensing technology (Mundt et al. 2006), but those relatively uncommon datasets are not initially proposed, as they complicate analyses and may limit the areas over which the metric would be adopted. The sagebrush cover type supports a variety of ecosystem services in the region, so rather than focusing on a specific service, a general change in sagebrush cover should be noted. Also, recovery of disturbed or destroyed sagebrush communities can take decades (e.g., Cooper et al. 2007). Therefore, relatively small changes in sagebrush cover will cause concern.

Field data: BLM personnel conduct qualitative and quantitative field surveys through their areas of interest (e.g., Pellant et al. 2005). These surveys include estimates of the percent of cover of shrubs and listing of dominant and subdominant land cover types. These data may contribute to estimating the percent of sagebrush cover.

Alternatives: Alternatives that would classify habitat suitable to sage-grouse with the relative ease and effectiveness of the percent of sagebrush cover are not available—the species is a sagebrush obligate. More detailed mapping of sagebrush cover, by different species or by size categories for example, is a possibility. Lek counts are an important indicator of sage-grouse population status. Extensive surveys would estimate sage-grouse density directly and reflect population status but are beyond the scope of the RMMP.

Indicator: **Old-growth pinyon-juniper woodlands** (patch number and acres)

Use: To characterize the quantity of habitats of special concern (3 in figure 2)

Spatial scale: Basinwide

Temporal scale: Intermittently updated as mapped or modified

Justification: Pinyon-juniper woodlands are an important land cover in the Colorado Plateau, including on the lands managed by the WRFO. Two concerns are cited by managers and others. Pinyon-juniper woodlands have expanded in range in response to fire suppression, release from past harvests, and land uses such as livestock grazing. This expansion decreases the amount of sagebrush and grassland habitat available (BLM, undated). Pinyon-juniper-expansion is unlikely to be associated with oil and gas development activities. The other concern, the preservation of very old stands of pinyon-juniper, is more likely related to oil and gas development activities. Stands with trees that are hundreds of years old are more structurally diverse than younger stands, are biologically diverse, and provide unique habitats, such as hollows for cavity-nesting birds. They also provide quantities of nuts and berries that are important food sources. These old stands tend to occur where the risk of fire is low and at sites of low productivity (Weisberg et al. 2008). Tracking changes in the amount and distribution of old-growth pinyon-juniper and including an old-growth stand map in the RMMP would be useful for planning.

Potential basis: Old-growth pinyon-juniper stands have proven difficult to map using computer algorithms that seek to identify patches within remotely sensed images. The most effective way of identifying old-growth pinyon-juniper stands is through fieldwork. Any existing digital spatial data for old-growth stands should be used and updated to include all mapped stands, with new stands added as they are located.

Field data: The perimeter of old-growth pinyon-juniper stands will be delineated using a global positioning system or indications on a map. The composition of the stand, such as mix of species, understory, and ages of trees, should be noted as well.

Alternatives: Alternatives to field mapping of stands are not known, although efforts to map old-growth pinyon-juniper stands using remotely sensed images will continue to develop. In general, the height and spectral distinction of the stands are not distinct enough to enable mapping. Very high-resolution images that are now available may allow for the complex structure of old-growth stands to be distinguished.

Indicator: **Vegetation composition** (percent cover and richness)

Use: To characterize long-term vegetation changes (3 in figure 2)

Spatial scale: < 100 m

Temporal scale: Repeated every 3-5 years (per site) and annually with remote sensing

Justification: Plant inventories are an important component of managing any terrestrial landscape and are mandated for federal lands under several pieces of legislation (e.g., Federal Land Policy and Management Act of 1976, Public Rangelands Improvement Act of 1978). Vegetation composition, aerial estimates, and heterogeneity provide critical measures of ecosystem conditions, processes, and relationships. These measures include biodiversity (Tilman et al. 1997), productivity (Kahmen et al. 2005), nutrient cycling (Hooper and Vitousek 1998), wildlife habitat (Sauls et al. 2006), invasions (Stohlgren et al. 2001), and fire risk (Evangelista et al. 2004). Most plant species are sparse, rare, and patchily distributed; as a result, detecting species occurrences and monitoring changes in vegetation composition generally requires frequent and intensive field surveys. For example, in a 6-year vegetation assessment that included intensive field surveys in southern Utah, Stohlgren and others (2005) found that more than 60 percent of the known flora was not detected in over 330 established field plots. This is especially concerning given the need to monitor plant diversity and successional trends, detect invasive species early, and manage ecosystem function. A systematic approach for conducting baseline inventories, monitoring along disturbance gradients, and ensuring reclamation success is needed. Initially, this approach will require intensive field surveys to record quantitative data on vegetation composition and site conditions. These data will be entered into the data management system cited previously. Once collected, these data can support multiple analyses that will better facilitate adaptive management strategies, support advanced sampling alternatives (i.e., remote sensing), and highlight spatial and temporal changes related to energy development while distinguishing them from other agents of change (e.g., climate, livestock grazing, and fire suppression).

Potential basis: Conducting systematic field surveys should include measurements that quantify species richness and percent foliar cover to maximize data utility (Stohlgren 2007). Average height by species may also be considered for estimating productivity, biomass, and fuel loads. Multiscaled nested plot designs have been demonstrated in numerous studies to be the most effective for detecting species occurrence and spatial trends (Stohlgren et al. 1995). Most field plots include measures of other site conditions and ancillary data that would be useful for additional proposed metrics. These measurements should include bare ground, standing dead, surface litter, biological soil crusts, and wildlife use, each providing important elements in monitoring vegetation composition and also contributing information that is valuable to other metrics related to oil and gas development. Plot locations and data analyses can be stratified by major vegetation types (e.g., sagebrush, pinyon-juniper), land use (e.g., grazing regimens, recreation), disturbance types (e.g., roads, pads), topography (e.g., slope, aspect), and others. Potential statistical analyses may be as simple as comparing species occurrences (by plot) over time to more complex geospatial models that model distributions across the landscape. Furthermore, georeferenced field data on plant composition will be required to test the applications of emerging remote sensing technologies, which are expected to be an alternative to field sampling for future monitoring.

Field data: Field sampling to inventory and monitor vegetation composition can be conducted using a number of potential methods and integrated into current BLM survey activities. Nested plot designs of at least two scales should be considered to maximize data quantity and quality (Barnett and Stohlgren 2003; USDA 2004). Field measurements and estimations should follow standard sampling protocols (Herrick et al. 2009; Stohlgren 2007) and include additional site conditions and ancillary data that may support different types of analyses (e.g., remote sensing). Consideration should be given to methods adopted by the Forest Service's Forest Inventory and Analyses (FIA) program (USDA 2004) or the National Resources Inventory (NRI) program (USDA 2009). The BLM has several vegetation monitoring projects already in place (e.g., rangeland health, long-term Daubenmire transects). Such datasets will provide valuable information on historic and baseline conditions on the landscape, but the methods may require modifications to meet increasing data needs and priorities related to oil and gas development.

Alternatives: Using remote sensing for detailed inventories and monitoring of vegetation composition is not currently a viable alternative to field surveys. The number of plants found in the Piceance Basin and high variability in densities and phenology can simply not be measured in detail using current remote sensing technology. However, a number of new sensors and methods currently being developed suggest that remote sensing applications may soon meet the proposed needs (Rocchini et al. 2005; Gillespie et al. 2008). Of particular interest is the use of rarefaction curves to measure spectral variation and estimate species richness within a given study area (Rocchini et al. 2009). These and other remote sensing approaches can be improved with high-resolution imagery, multiple bands, and seasonal data acquisition, all recently developed by the BLM using multiple platforms (i.e., QuickBird, RapidEye, and NAIP). New technologies in remote sensing, coupled with new innovative analyses, will likely provide a superior means to surveying vegetation across spatial and temporal scales in the near future.

Indicator: **Surface disturbance,** consisting of:

Road density (mile/section)
Well-pad density (pads/section)
Distance to roads and wells (per pixel)
Pipeline density (mile/section)
Area disturbed (acres/section)
Total area disturbed (acres)
Area reclaimed (acres/section, interim and final)
Total area reclaimed (acres, interim and final)
Well-pad status (categorical, per well)

Use: To characterize disturbance by oil and gas extraction activities, levels of fragmentation, and reclamation associated with oil and gas extraction (1 and 7 in figure 2)

Spatial scale: Variable, depending upon metric

Temporal scale: Updated with each proposed and approved use

Justification: Oil and gas development activities may have direct or indirect effects on the behaviors of wildlife and other ecosystem attributes. Roads may be barriers to animal movement, subdivide populations, and reduce habitat both directly and through disturbance. Roads and the traffic they bring may disturb wildlife or alter roadside habitats, limit the movements of animals, increase access to landscapes for recreationists (with results that are positive or negative, depending upon perspectives), and reduce the aesthetics of landscapes to humans (reviewed in Forman and Alexander 1998; Spellerberg 1998). Research into response of wildlife to nearby roads is extensive (e.g., Oxley et al. 1974; Rost and Bailey 1979; Cole et al. 1997; Forman 2000; Lodé 2000; Dyer et al. 2002; Epps et al. 2005; Jaeger et al. 2005; Thomson et al. 2005; Ouren et al. 2007; Frair et al. 2008; Sawyer et al. 2009). Road networks can become quite dense, with the ecological footprint of their effects overlapping (Frair et al. 2008). The effects of changes in access include increased disturbance, weed spread (Lonsdale and Lane 1994; Zwaenepoel et al. 2006), and decreased opportunities for solitude during recreational activities.

The commonalty among these metrics is that they may be calculated directly from spatial information that will be stored within a GIS. As oil and gas extraction plans are reviewed by the WRFO, the proposed infrastructure may be incorporated into a GIS and these metrics recalculated to help judge potential effects.

Potential basis: An extensive spatial database is available for the study area and is currently being updated, and new or proposed infrastructure may be added easily. Status reports come from oil and gas production companies or from field visits by BLM personnel. Calculating these metrics is then a spatial database management exercise.

Field data: Infrastructure is incorporated into the geodatabase in use by the BLM. New and proposed infrastructure, with attributes reflecting their type and frequency of use, will be provided by energy enterprises or digitized from high-resolution remotely sensed images.

Alternatives: Road networks and other oil and gas extraction infrastructure are frequently used in wildlife and landscape ecology research as a direct measure of disturbance and fragmentation or a surrogate. Given that spatial data are developed by the BLM as a routine part of oil and gas development authorization and other development in the Piceance Creek Basin, better alternatives are not available. However, weightings may be assigned to different kinds of disturbances as their potential effects are synthesized (e.g., a main roadway versus a rarely used two-track). Alternative weightings and buffers of disturbance may be explored.

Indicator: **Road traffic** (vehicles/day)

Use: To characterize disturbance (1 and 7 in figure 2)

Spatial scale: Road traffic summarized for monitored corridors

Temporal scale: Reported continuously

Justification: Road traffic may have direct or indirect effects on the behaviors of wildlife. Roads increase mortality through vehicle collisions and reduce habitat both directly and through disturbance. Conover and others (1995) estimated that in the United States, vehicle collisions with deer caused $1.1 billion in damage. Accidents involving fatalities have steadily increased (119 per year from 1993 to 1997, 155 per year from 1998 to 2002, and now are estimated at 210 deaths per year) (IIHS 2009). Many deer, elk, and other animals die from collisions, in some areas so often that population effects are evident. In areas with oil and gas extraction activities, the risk of disturbance from vehicles may be quite high; Kuhn (2006) estimated that in northeastern Utah, each new well required trucking between 375 and 1,375 loads of materials, supplies, and equipment. Additionally, operating wells must be visited, although advances in technology make those visits less frequent (Sawyer et al. 2009).

Road traffic may disturb wildlife or alter roadside habitats and reduce the aesthetics of landscapes to humans (reviewed in Forman and Alexander 1998; Spellerberg 1998). Research into the response of wildlife to nearby roads is extensive (e.g., Oxley et al. 1974; Rost and Bailey 1979; Cole et al. 1997; Forman 2000; Lodé 2000; Dyer et al. 2002; Epps et al. 2005; Jaeger et al. 2005; Thomson et al. 2005; Ouren et al. 2007; Frair et al. 2008; Sawyer et al. 2009), and the effects of dust on vegetation from nearby roads have been explored in other areas (e.g., Walker and Everett 1987; Ndibalema et al. 2007; Fahrig and Rytwinski 2009). The effects of changes in access include increased disturbance, the spread of weeds (Lonsdale and Lane 1994, Zwaenepoel et al. 2006), and decreased opportunities for solitude as part of recreational activities.

Potential basis: Road traffic monitoring sensors are proposed for key travel corridors within the Piceance Creek Basin. Advanced monitoring systems are available that use components such as in-car GPS receivers, but if the devices were placed in industry vehicles, the approach would only quantify a portion of traffic. Systems using cameras may be effective (Atkočiūnas et al. 2005), and traffic may even be quantified from satellite images. Regardless, the use of a standard cabled vehicle counter and classifier system is proposed. These systems provide information on axle count, speed, and other data, which may be used to infer vehicle type.

Field data: Road traffic will require monitoring devices and reports of vehicle control features (e.g., gating) from the field.

Alternatives: The travel management plan for the region is being updated by the WRFO, which may alter the nature of monitors and will influence the travel corridors proposed for monitoring.

Indicator: **Particulate matter** (size-resolved concentrations)

Use: To characterize atmospheric pollution (8 in figure 2)

Spatial scale: Point-based

Temporal scale: Reported continuously, every 24 hours, and annually

Justification: Particulate matter of greatest concern is generated by vehicles, roadside activities, industry, and other disturbances and is classified into two categories: fine and coarse particles. Fine particles are those in smoke and haze that are less than 2.5 micrometers ($PM_{2.5}$), and the greatest health concern. Particulate matter of this size can be inhaled deeply into the lungs and cause increased respiratory problems, such as irritation, coughing, bronchitis, and aggravated asthma. For those with compromised pulmonary or respiratory systems, exposure to high $PM_{2.5}$ concentrations can cause premature death (EPA 2009). Coarse particles are those that are larger than $PM_{2.5}$ but less than 10 micrometers (PM_{10}). These remain a human health concern, but are not inhaled as deeply into the lungs. Particles greater than 10 micrometers, such as sand and coarse dust, have not been related to human health concerns and are not monitored by the Environmental Protection Agency (EPA).

In addition to problems related to human health, particulate matter makes the atmosphere hazy, reducing the aesthetic appeal of landscapes. Haziness at national parks is an ongoing problem (NPS 2002). Particulate matter can lift into the atmosphere and travel long distances. Particles may be inhaled by people distant from the pollution source or may settle on plants, reducing their productivity; in water sources, increasing their acidity; on buildings or other structures, causing damage to them; or on snow, increasing its melt rate (Flanner et al. 2009).

Potential basis: Particulate matter is measured at scattered locations throughout western Colorado. Monitors for $PM_{2.5}$ or PM_{10} are in place in Delta, Parachute, Clifton, Rifle, Grand Junction, and Cortez, plus new sensors are in place in Meeker and Rangely. Standards for fine ($PM_{2.5}$) and coarse (PM_{10}) particulate matter concentration are defined by the EPA under the Clean Air Act. The standards are formally defined and include both annual (for $PM_{2.5}$) and 24-hour averaging time. See EPA (2009) and documents therein for more detail, but in general, formulas are used to determine if PM_{10} exceeded 150 $\mu g/m^3$, averaged over 24-hour periods, and if $PM_{2.5}$ exceeded 15 $\mu g/m^3$ annually or 35 $\mu g/m^3$ over 24 hours.

Field data: These data are gathered from EPA designated monitoring sites. No further field data are needed.

Alternatives: Particulate matter has a long history of being both a concern and a monitored pollutant in the United States. Alternative measures are not suggested.

Indicator: **Ground-level ozone concentration** (parts per million)

Use: To characterize atmospheric pollution (9 in figure 2)

Spatial scale: Point-based

Temporal scale: Reported continuously, every 8 hours, and annually

Justification: Kilometers above the earth's surface, in the stratosphere, ozone helps protect humans and ecosystems from the sun's ultraviolet rays. But at ground level, ozone is a pollutant that is a danger to humans and other organisms (Royal Society 2008). Ground-level ozone is created through chemical reactions between the nitrogen oxides and volatile organic compounds found in vehicle exhaust, industrial emissions, and natural sources (EPA 2009). Ozone is a major component of smog and is a respiratory irritant, causing coughing, inflammation, and other breathing difficulties in humans. Ozone aggravates asthma, can permanently harm lungs with repeated exposure, and increases death rates with chronic exposure (Jerrett et al. 2009). Ozone also affects plants and animals. It can damage the leaves of plants, can reduce growth rates and crop yields, and may decrease biodiversity (e.g., Fuhrer and Booker 2003; Royal Society 2008).

Potential basis: In western Colorado, ozone sensors are operated in Rifle, Palisade, and Gothic (CDPHE 2008), and two newly established monitoring stations are located in Meeker and Rangely. Given the plans for oil and gas extraction in the Piceance Creek Basin, an ozone monitor that is equivalent to those used by the EPA would be beneficial near the center of oil and gas activities in the WRFO.

Three metrics would be reported: instantaneous ozone concentration (stored through time), the number of measurements within each 8-hour period that exceed the threshold, and the number of times the threshold is exceeded annually. Standards for ground-level ozone concentration are defined by the EPA under the Clean Air Act, and were updated in 2008. The standards are formally defined and include multiyear averages of 8-hour peak concentrations, but in essence, they require that ozone should not exceed 0.075 ppm at peak periods.

Field data: Additional field data, beyond the information reported by the monitors, is not required.

Alternatives: Other pollutants may be measured, rather than ozone. Nitrogen oxides and volatile organic compounds contribute to ozone production. However, ozone has been demonstrated to have direct effects on human health and a modest monitoring network is in place in Colorado.

Indicator: **Landscape spatial pattern,** consisting of:

Shape complexity (a dimensionless index)	Like adjacencies (percent)
Edge contrast (index)	Nearest neighbor distance (meters)
Core area (acres)	Patch isolation (meters)
Large patch dominance (percent)	Connectance (index)

Use: To characterize landscape patterns and the patterns of habitats used by species of management concern (4, 5, and 7 in figure 2)

Spatial scale: 30-m resolution or finer

Temporal scale: Updated with each change, or proposed change, in infrastructure; land cover map updated annually

Justification: In addition to the composition of habitat areas available to wildlife (addressed under the "Vegetation composition" indicator), the spatial pattern (e.g., connectivity, patch complexity, etc.) of habitats within landscapes plays an important role in the survival and productivity of animals. Animals that migrate, such as mule deer in the Piceance Basin, have higher survival rates if suitable habitat is available along the migratory pathway (Berger 2004). An important class of landscape metrics, dealing with connectivity*,* addresses the concern of migratory pathways. Some wildlife species are edge species, meaning they are associated with areas where two kinds of habitat come together. A square landscape patch (of a given area) would provide edge species with less habitat (because of relatively minimal "edge") as compared to a patch with a complex shape, resulting in a great deal of edge. Two more suites of metrics capture patch complexity (i.e., shape) and the related contrast between habitats at edges. Contrast indicates the difference in habitat types at a patch edge. For example, contrast between deciduous forest and mixed conifer-deciduous forest may be low, and contrast between deciduous forest and bare ground would be high. Lastly, some species favor large tracts of intact or undisturbed habitat, such as several species of nesting neotropical migratory birds. Landscape metrics that capture core area are therefore helpful to distinguish habitats (of a given area) that occur in scattered patches from habitats that may be in a single, contiguous large patch. Scientists and land managers seek landscape metrics that capture these and other habitat attributes and metrics that more generally provide an indication of changes in landscape pattern over space and time.

Landscape ecologists have devised many indices of landscape pattern, but most of these have been shown to be highly correlated; that is, two measures may be measuring the same thing in different ways (Riitters et al. 1995; Hargis et al. 1998; Cushman et al. 2008). Cushman and others (2008) tested 54 metrics on three landscapes, and judged 7 metrics to be both consistent and broadly applicable in capturing different aspects of the landscapes. Five of those metrics are appropriate for inclusion into the RMMP, as are three additional measures that are correlated with the metrics studied by Cushman et al., but that are more easily interpreted. The metrics are grouped into four general classes and their definitions are drawn mostly from McGarigal and others (2002:

Complexity

Shape complexity is a widely used metric, where the complexity of each patch in the landscape is represented by the ratio of the perimeter of the patch compared to the perimeter of a patch of equal area, if it were a square (Patton 1975). The mean of those values will be calculated as well to yield a landscape-level metric. As the perimeter of a patch becomes more convoluted, this ratio increases, and in turn, as a patch shape approaches a square, the ratio approaches 1.

Edge contrast uses spatial layers and additional information. Analysts assign similarity indices to land cover types. For example, a mixed oak-maple class may be assigned high similarity to a cottonwood class, moderate similarity to a juniper class, and very low similarity to an industrial class. The edge contrast index then summarizes the contrast between the edges of adjoining patches, with a landscape dominated by patches that are similar approaching 0 percent, and a landscape with very different abutting classes approaching 100 percent.

Core Area

Core area reports the "interior" area for individual patches, or the total core area for a landscape, where the interior area is defined as land within patches that is a given distance from either the edge of inhospitable patches or sources of disturbance.

Large patch dominance is the area of land in a landscape that comprises the largest contiguous patches of a given land cover type, divided by the entire area of that given type, converted into a percentage. For a given patch type, many small evenly spaced patches would yield values approaching 0 percent for the largest patch on the landscape, and if most of the area of a given patch type was in one patch, it would approach 100 percent for that large patch.

Contagion

Like adjacencies is a metric that compares the number of adjacent landscape cells that are of the same type against the total number of cells adjacent to the focal type, regardless of their type. If landscape cells are clustered together (i.e., have high contagion) the percentage will be high. If cells are highly dispersed, the percentage will be low. In essence, the metric is reflecting fragmentation of different land cover types at the pixel level.

Connectivity

Nearest neighbor distance is a reflection of patch isolation, the mean distance between the centroid of a given habitat patch and its nearest neighbor. From patch-level distances, a landscape-level mean of nearest neighbor distance may be calculated.

Patch isolation is a measure of the variability in nearest neighbor distances among patches of the same type, reflecting the degree to which patches are distributed across a landscape, converted to a percentage. For land cover types that have uniformly short nearest neighbor distances, the index approaches 0 percent. For those where the types are clumped on the landscape in dispersed patches, the index approaches 100 percent.

Connectance is based on the number of patches of a given type that are within a specified distance in a landscape, compared with the total number of patches of that type in the landscape. If patches of a given type are farther away, the connectance index declines.

Direct linkages have been made between changes in complexity, core area, contagion, and connectivity and changes in populations or behaviors of wildlife. For example, working in Austria, Moser and others (2002) demonstrated a linkage between patch shape complexity and plant species richness. Australian bird richness has been linked (weakly) to patch shape complexity (Radford et al. 2005). Core area metrics have been derived to quantify high-quality habitat for species that avoid edges, such as forest-interior nesting birds (e.g., Laurance and Yensen 1991). Species that occur within the Piceance Creek Basin have been shown (elsewhere) to avoid disturbed areas, such as sage-grouse avoiding oil and gas development activities (Aldridge and Boyce 2007; Doherty et al. 2008; Holloran et al. 2010; discussed in Kotliar et al. 2008) and mule deer avoiding roads or well pads (Rost and Bailey 1979; Sawyer et al. 2006; Sawyer et al. 2009). Connectivity has been explicitly considered in planning for greater sage-grouse in Oregon (Hagen 2005). Literature suggests that patches that are nearby one another (i.e., more connected) are expected to be used more than patches that are distant (MacArthur and Wilson 1967, reviewed in Bender et al. 2003). Regarding focal species in the Piceance Creek Basin, a report states that greater sage-grouse select for more complexly shaped patches for nest sites (Petersen et al. 2009), whereas general habitat quality for sage-grouse declines as edge-to-area increases (Hagen 2005, addressed more generally in Crawford et al. 2004). Elk use has also been shown to be positively related to the shape complexity of the meadows they use in summer (Stubblefield et al. 2006). More generally, large herbivores must access different patches to acquire sufficient forage (e.g., Boone 2007). Demonstrations of wildlife avoidance of roads, traffic (Dyer et al. 2002; Epps et al. 2005; Jaeger et al. 2005; Gavin and Komers 2006; Frair et al. 2008), and oil and gas extraction activities (e.g., Bradshaw et al. 1997; Lyon and Anderson 2003; Berger 2004; Sawyer et al. 2006; Aldridge and Boyce 2007; Walker et al. 2007; Copeland et al. 2009; Sawyer et al. 2009), or of the benefit that any landscape treatment may provide to mitigate the effects of fragmentation, provide justification for the utility of capturing habitat isolation metrics.

Potential basis: Metrics can be calculated based on habitat maps created using two major sources. The first is the land cover map that is being developed by the WRFO, using 5-m resolution RapidEye satellite imagery. Habitat maps for selected species can be created from habitat associations agreed upon by collaborators, but will be similar to those used in Colorado Gap Analysis (CO-GAP 2001). Focal species include deer, elk, and sage grouse, with the possibility of list expansion if needed. For these habitat maps, areas that are within buffers (buffer distances yet to be determined) around sources of disturbance can be excluded from calculations to capture potential behavioral effects.

Landscape indicators can also be calculated for the full land cover map. The results of these calculations can be helpful in two ways. First, they can characterize changes in landscape pattern that serve as habitat for other species not listed here (Boone et al. 2008). Second, the results can identify changes in spatial patterning of selected plant communities. Communities of interest include pinyon-juniper, old-growth pinyon-juniper, and sagebrush, broken into the three predominant species of sagebrush in the WRFO.

For the metric calculations specific to habitat, the focus is on habitat suitability (i.e., how suitable it is for an animal's use); therefore, the different land cover types can be merged to create a "suitable" versus "unsuitable" habitat layer. Then for all maps, indicators can be calculated for suitable habitats at the patch level, yielding maps showing metric values spatially, and at the landscape level, yielding a single value for a landscape.

Field data: Landscape structure metrics are calculated based on the patterning of available spatial data and do not require further field-collected data for their creation.

Alternatives: These metrics, like any, cannot capture all that is of interest regarding landscape pattern (e.g., Bender et al. 2003), but in concert with the other metrics in the RMMP, and with support from the literature, they can provide a comprehensive representation in the RMMP. In future versions of the RMMP, areas of interest may be defined that are subsets of the entire landscape (e.g., hilltops or particular management units), and landscape-level metrics can be calculated based on those subsets.

Indicator: **Invasive plant species** (percent cover and richness)

Use: To characterize extent and distribution of invasive species (3 in figure 2)

Spatial scale: < 100 m

Temporal scale: Field sampling every 3-5 years (per site); annually with remote sensing

Justification: Direct and indirect effects of invasive species on native species and ecosystem processes are wide ranging and well documented in the scientific literature. Most invasive species exhibit unique physiological traits that provide them with a competitive advantage over their native counterparts. These traits may enhance an invader's ability to exploit resources, survive under adverse conditions, successfully reproduce, or modify ecological conditions to their advantage. Road and infrastructure construction associated with oil and gas development has been implicated as a major conduit for new invasions (Bergquist et al. 2007) while providing conditions that facilitate the dominance of these species. Clearing of vegetation and topsoil creates ecological niches by improving accessibility to water, sunlight, and soil nutrients (Trombulak and Frissell 2000), and vehicles transport seeds that are dispersed along roadsides (Schmidt 1989; Lonsdale and Lane 1994). Once established, invasive species typically are more resilient than native species and continue to survive in disturbed areas and roadsides. Mowing, herbicide treatments, and soil compaction often prevent the reestablishment of natives while having only minimal effects on invaders (Forman and Alexander 1998, Gerbard and Belnap 2003).

Of particular concern is cheatgrass (*Bromus tectorum),* a fast-growing annual grass that has invaded rangelands throughout the West and has already become moderately established in the Piceance Basin. Cheatgrass germinates during winter months, prior to most native annuals, allowing early root development that can quickly exploit soil nutrients and water (Skipper et al. 1996). The species is also tolerant to grazing, drought, poor soils, and other conditions that may be detrimental to native species, and most notably, is has a positive response to fire. The species produces considerably more aboveground litter than native species, increasing the probability, extent, and severity of fires (West 1983, D'Antonio and Vitousek 1992, D'Antonio 2000). This in turn modifies site conditions to be more favorable for cheatgrass and often results in large-scale monocultures. Other high-priority invasive species are leafy spurge (*Euphorbia esula*) and Russian knapweed (*Acroptilon repens*), which have already become well established in the Piceance Basin. Like cheatgrass, further infestations of these species may be facilitated by activities related to oil and gas development.

Potential basis: Detection and monitoring of invasive species require vigilance, especially within close proximities to developing infrastructure and at reclamation sites. Field sampling (see the vegetation composition indicator section) can provide quantitative data that allows for plot-level comparisons across spatial and temporal scales and can be used for training of remotely sensed imagery. Species richness measurements can provide a means for early detection of new arrivals while allowing resource managers to monitor and predict spatial distributions of invaders that have already established (Stohlgren 2007). The percent of cover that an invasive species occupies can serve to measure species dominance (Crall et al. 2006) and provide baseline field data that can be used to determine spectral signatures for specific species of concern. Plot data can also be stratified by vegetation or disturbance types (including reclamation) and used to identify community-level changes and risks (Bergquist et al. 2007). Field sampling alone may not be adequate for early detection of invasive species. Occurrences of invasive species should be recorded whenever opportunity allows. Georeferenced occurrences (e.g., coordinates collected with GPS) can supplement datasets required for remote sensing applications and assess distribution patterns.

Only a few invasive species have been successfully measured using remote sensing techniques; of these, most either occur as large monocultures or are shrub and tree species that have greater visibility. Invasive grasses and forbs are more difficult to detect and require high-resolution imagery collected throughout the growing season. Populations and distributions of invasive species should be expected to respond positively to oil and gas development if left unchecked (Bergquist et al. 2007). In a few studies, cheatgrass was distinguished from other vegetation using time-series data collected from various remote sensing platforms (Bradley and Mustard 2005, Peterson 2005). In these cases, cheatgrass infestations were extensive. However, given the unique phenology of cheatgrass and the availability of high-resolution, multispectral imagery, the ability to detect invasive species using remote sensing is rapidly improving. Examples can be found with yellow starthistle (Miao et al. 2006), spotted knapweed (Lass et al. 2002), tamarisk (Evangelista et al. 2009), and others. The methods may not yet be applicable for early detection or low densities, but they should be considered for monitoring infestations across the landscape, along disturbance gradients, and at reclamation sites.

Field data: Field surveys aimed at detecting and monitoring new invasions should be integrated with efforts to measure native vegetation composition (see the vegetation composition indicator section). Monitoring for invasive plant species can also occur during compliance visits in the field at production sites, reclamation sites, and pipeline rights-of-way. As previously mentioned, there are a number of plot designs and sampling strategies that can be used for collecting field data and for training of remotely sensed imagery (Barnett et al. 2007; Herrick et al. 2009). Sampling protocols should follow those outlined by Herrick and others (2009) and other widely accepted standards (e.g., North American Weed Management Association at www.nawma.org; National Institute of Invasive Species Science at www.niiss.org).

Alternatives: Remote sensing alone is an alternative for monitoring large infestations, but it is currently inadequate for early detection of new invasive species. Remote sensing initiatives recently implemented by the BLM will greatly improve detection capabilities and can augment field sampling now and in the future. Spatial modeling has proven to be an effective tool for predicting the potential spread of new invaders and highlighting areas at risk on the landscape (Evangelista et al. 2008). These methods still require intensive field surveys initially, but surveys can be scaled down as new methods are developed.

Indicator: **Water quality,** consisting of:

Dissolved solids (parts per million)
Dissolved oxygen (parts per million)
Metals concentration (parts per million)
Suspended sediments (turbidity units)

Use: To characterize water quality (6 in figure 2)

Spatial scale: Point- or reach-based

Temporal scale: Monthly and annually

Justification: Water quality is included here because it is an excellent integrator, reflecting the condition of the watershed and its underlying aquifers. The quality of the water in a creek or stream is a reflection of conditions in the watershed through which the water flowed. Water quality within the Piceance Basin is highly variable, largely due to differences in geology and flow regimes (EPA 2004). Base flows of annual streams come primarily from bedrock aquifers, which tend to reflect the chemistry and geologic parent material and are of low quality (EPA 2004; CDOW and USFWS 2007). Surface runoff is generally from spring snowmelt and intense rain events. As a result, sediment loads are high (Andrews 1983) and of low quality due to the presence of sodium bicarbonate and salts (EPA 2004). Drinking water is only available from shallow waters and wells (< 200 feet), thus it is a critical resource for residents of the area (EPA 2004). Coproduced water from methane extraction can be particularly poor in quality (Rice et al. 2000; Stearns et al. 2005), and can only be disposed of in evaporation ponds or by reinjection in the Piceance Basin (EPA 2004).

Surface disturbances caused by various activities related to oil and gas development have been reported to alter soil chemistry and nutrient composition (Bergquist et al. 2007). Modifications at the soil surface can in turn be transported by surface runoff and accumulate in streams, wetlands, and lowlands and circulate with shallow groundwater. Because of the limited potable water and pollutants contributed by other natural and anthropogenic activities (e.g. agriculture), water quality should be monitored frequently and intensely.

Potential basis: A number of water quality studies are currently being facilitated by the BLM, USGS, Colorado Oil and Gas Conservation Commission (COGCC), and oil and gas operators in the Piceance Basin. Some of these studies have been implemented for several decades (http://waterdata.usgs.gov/nwis/nwis), while others have been recently developed to address baseline data needs (http://rmgsc.cr.usgs.gov/cwqdr/Piceance/). Most analyses include major cations and anions, water quality parameters, metals, volatile and semivolatile organic compounds, and other dissolved minerals and suspended sediments.

Field data: Currently, there are a number of water quality studies and monitoring programs for surface water and groundwater. Additional field data may be required; however, previously collected baseline data and existing studies may be sufficient. Notable changes in water quality data and proposed sites for development should serve as a guide for additional data collection.

Alternatives: Additional field sampling may be required to identify sources of dissolved minerals and suspended sediments. These efforts may be conducted in collaboration with the USGS or with oil and gas operators. Remote sensing applications are commonly used to detect changes in turbidity, sediment deposition, inundation, and lateral shifts in stream channels (see reviews by Smith 1997; Pavelsky and Smith 2009) and should be considered as a monitoring tool in the Piceance Basin.

Indicator: **Mule deer fawn:doe ratio** (number per 100 does)

Use: To characterize landscape suitability for big game (5 in figure 2)

Spatial scale: Colorado Division of Wildlife (CDOW) Data Analysis Unit (DAU)

Temporal scale: Annually

Justification: Wildlife managers have identified different means of monitoring the performance of deer herds. Surveying the number of adults, especially the number of does, seems like a measure of success. However, female deer survival is generally fairly high and not very sensitive to year-to-year variations in conditions. One measure that has proven effective is the fawn:doe ratio. Does may produce fawns in good years, and in other years, they may not. A variety of conditions may affect doe productivity, such as forage availability, predation rates, weather, body condition, stress from raising a fawn the previous year, and disease. As such, the fawn:doe ratio is a metric that integrates a series of effects on populations.

Potential basis: The CDOW estimates fawn:doe ratios based on aerial and ground surveys. Winter flights are conducted, with observers counting, sexing, and aging deer observed. From these data, ratios are calculated. The completeness of counts is dependent, in part, on snow cover, which increases the visibility of deer. A negative of this metric is that changes in snow cover from year to year can increase its variability.

Field data: Ratios can be calculated based on surveys and simulations conducted by the CDOW, using methods they deem most appropriate.

Alternatives: Buck:doe ratios may be helpful, although those are more closely related to harvest histories and management than to the suitability of landscapes to support females producing offspring, as in the fawn:doe ratio. Population modeling is conducted by the CDOW, and the fawn:doe ratio is a factor in the analysis. In years when the ratio is unavailable, simulation output may be used, with appropriate notation. More generally, these data are regularly collected by the CDOW, and provide an indication of changes in habitat quality for mule deer within the Piceance Creek Basin. Given that the data are available, other alternatives are not suggested. However, during years when the CDOW does not have funds for the basin to be surveyed aerially, financial support from the energy industry or the BLM may make a survey possible, which would be beneficial to the RMMP.

Indicator: **Lek counts** (number)

Use: To characterize population trend of species of special interest (4 in figure 2)

Spatial scale: Basinwide

Temporal scale: Annually

Justification: Quantifying potential habitat availability for sage-grouse has been proposed. The RMMP should also include information already collected that provides a more direct estimate of trends for sage-grouse, such as results from lek counts in the Piceance Creek Basin. Leks are the breeding areas where male sage-grouse return each year to dance and attract females. Biologists within the range of sage-grouse count known leks, seek out new leks, and conduct several counts of the number of birds seen during the breeding period. There are numerous assumptions and issues that must be considered when interpreting lek counts (reviewed in CGSSC 2008), but in general, some areas have had counts in place for 50 years, and they have been shown to be useful indicators of population size, although standardization of methods is encouraged (Walsh et al. 2004).

Potential basis: Lek counts are conducted semiannually by CDOW personnel and supplemented by counts from BLM staff. These count results form the basis for this metric, or trend, within the RMMP. Total sage-grouse estimates, rather than actual counts, for the Piceance Creek Basin may be recorded in the RMMP.

Field data: Population estimates are based on counts on leks, using methods established by the CDOW.

Alternatives: Alternative methods of estimating population size are available (CGSSC 2008), but deciding upon best practices is the purview of the CDOW. More generally, a direct estimate of the sage-grouse population over time for the basin is useful; these data are available without additional cost, so alternatives are not suggested.

Indicator: **Selected songbird abundances** (index)

Use: To characterize population trend of species of special interest (5 in figure 2)

Spatial scale: Point-based at areas of interest

Temporal scale: Annually, in the spring

Justification: A component of the BLM's mission is to maintain biological diversity on the public lands it manages. Land managers therefore track the general trends of species populations, including songbirds. Three species of songbirds of conservation concern, as listed by the U.S. Fish and Wildlife Service, or management interest were selected by WRFO personnel for survey. In general, these species were selected because they are in sufficient abundance to allow typical point counts to yield abundance trends: gray vireo (*Vireo vicinior*), sage sparrow (*Amphispiza belli*), and Brewer's sparrow. Gray vireos are small birds with subtle coloration that most often inhabit pinyon and juniper woodlands and other brushy habitats on midslopes. These vireos breed in western Colorado and other southwestern states and winter in Mexico. Sage sparrows are medium-sized sparrows that breed primarily in WRFO's lower elevation sagebrush and salt desert communities. Sage sparrows breed and summer in Colorado and winter in areas of the Great Basin west and south of Colorado. Brewer's sparrows are also midsized and breed in Colorado and other western states, extending into Canada. They migrate to the southern United States and Mexico in winter. Brewer's sparrows are confined to various big-sagebrush habitats in northwest Colorado.

Results from the USGS North American Breeding Bird Survey (BBS) show gray vireos declining in Colorado from 1966 to 2003 at more than 1.5 percent per year (Sauer et al. 2008; the extremes in population change in these maps are -1.5 percent and +1.5 percent per year). Trends for Brewer's sparrow are strongly negative overall in Colorado. Their population trend varies spatially, with populations declining at more than 1.5 percent per year for the western slopes of Colorado and the eastern plains, but increasing at greater than 1.5 percent per year in the Rocky Mountains. Populations of sage sparrow are stable overall in Colorado, according to the BBS, although the pattern of change is more complex than for the other species and shows declines in the northwestern part of the state (Sauer et al. 2008).

Potential basis: BLM personnel are conducting annual point counts for the three species of interest in areas of suitable habitat where they may be disturbed by oil and gas extraction activities. These surveys should continue and be expanded to the degree practical to capture potential effects of oil and gas extraction disturbance on these songbirds.

Field data: For areas of interest identified by BLM managers, point counts are conducted in the spring. A person skilled in bird identification by sight, and especially by sound, looks and listens for a period (often 3 minutes), recording all the birds seen or heard during that time.

Alternatives: There are five active BBS routes in the area managed by the BLM WRFO; one is fully within WRFO-managed lands and four that are partially included. In addition, two other surveys include other parts of the Piceance Basin that are in close proximity of the WRFO. These surveys are not ideal to capture potential changes in bird abundance related to oil and gas development activities. The routes are placed on secondary roads often far from oil and gas development. The surveys described here, which adopt BBS techniques for the points sampled, are placed in areas specifically because of the distribution of disturbance. Given that bird surveys are rapid and effective in indicating population changes over sufficient time, no alternatives to these metrics are suggested.

Indicator: **Biological soil crusts** (percent cover and age-class)

Use: To characterize changes in soil biology, extent of crusting, and disturbance (1 and 2 in figure 2)

Spatial scale: < 100-m field plots (incorporate with vegetation composition)

Temporal scale: Repeated every 3-5 years (per site)

Justification: An important property of soils found in semiarid regions throughout the western United States is the presence of biological soil crusts. Composition of soil crusts is a complex assemblage of microorganisms dominated by cyanobacteria, algaes, lichens, and mosses. Concentrated in the top 1 to 4 mm of soil, soil crusts primarily affect processes that occur at the land surface or soil-air interface (Belnap 1996). In semiarid ecosystems, soil crusts function to increase soil stability, control erosion from wind and water, fix atmospheric nitrogen, contribute nutrients to neighboring plants, provide positive soil-plant-water relations, enhance seed germination, and stimulate plant growth (Anderson et al. 1982a, 1982b; Belnap and Gardner 1993; Belnap and Gillette 1998a, 1998b). Growth and development of soil crusts are generally slow processes, and crusts may take 80 to 100 years to reach full development (Anderson et al. 1982a). The fragile structure of soil crusts causes them to be extremely susceptible to surface disturbances, which puts them at risk from road development, pipelines, pad construction, and other activities related to oil and gas development. Depending on the type of disturbance and site conditions, recovery for well-developed crusts may take hundreds of years (Belnap 1996; Evangelista et al. 2004). Disturbances to soil crusts can impede nitrogen fixation capabilities, which could potentially affect the nitrogen budget throughout an ecosystem, resulting in shifts in floral composition and invasion of nonnative plants (Belnap 1995, 1996; Evans and Johansen 1999). Loss or degradation of soil crusts may also result in decreased water availability to plants, accelerated wind and water erosion, decreased plant diversity and soil biota, and slowed decomposition of soil organic matter (Belnap 1995, 1996; Evans and Johansen 1999).

Potential basis: West (1990) broadly divided the organism composition of soil crusts into two categories: those that are microscopic (e.g., algae, fungi, and bacteria), and those that are visible to the human eye (e.g., lichens and mosses). Although direct field observations of the microscopic organisms are limited, their presence creates small-scale topographic features at the soil surface that are visually apparent. Based on physical characteristics, several studies have developed and tested simple classification indices that can be used by resource managers to visually measure and assess the development and condition of biological soil crusts in the field (Evangelista et al. 2004; Belnap et al. 2008). Height, structure, and coloration of crusts have been found to be highly correlated with chlorophyll and pigment content and may be easily incorporated in the field without costly laboratory analyses.

Field data: These measurements should focus on areas that are in the process of reclamation and within close proximity to infrastructure related to extraction activities. Because field observations can be conducted rapidly, additional measurements may be integrated with surveys targeting native vegetation composition (see vegetation composition indicator section) providing opportunities for comparative studies. The presence of crusts is already recorded with existing BLM projects (e.g., rangeland health, long-term Daubenmire transects). Modifications of existing field efforts would require additional measurements that quantify crust development and condition (e.g., percent cover, developmental stages). An increased number of sampling sites and monitoring periods will be needed in areas open to oil and gas development and following reclamation efforts.

Alternatives: There are few remote sensing alternatives for measuring and monitoring biological soil crusts for the Piceance Basin. Several studies using remote sensing techniques have had promising results (Anderson and Kuhn 2008; Ustin et al. 2009); however, most of these tests were conducted as controlled experiments or in arid regions with minimal vegetation. Despite high-resolution and multiband remote sensing capabilities, topography and vegetation structure will likely prevent these approaches from being considered as an effective alternative in the near term. Efforts to test new methods for measuring soil crusts using high-resolution remote sensing should be considered.

Glossary

Adaptive management: "A decision process that promotes flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood. Careful monitoring of these outcomes both advances scientific understanding and helps adjust policies or operations as part of an iterative learning process. Adaptive management also recognizes the importance of natural variability in contributing to ecological resilience and productivity" (USDI 2008)

Anthropogenic: Resulting from the influence of human beings, loosely meaning human caused or human made.

Classification: The assignment of items or landscape elements into classes based on shared similarities (adapted from Bedell 1998).
Classification accuracy: For satellite images classified into categories, the degree of agreement between the class assigned to a location in the image, and the class assigned to the location on earth through some means considered "truth," such as through field visits. This is a crude measure of accuracy, with more refined measures incorporating errors such as omission and commission.

Cover: The proportion of a landscape area that is occupied by vegetation or a specific type of variation, living or dead (adapted from Bedell 1998).

Disturbance: Changes in vegetation cover and the altering of top soil done by humans. For example, oil and gas extraction can include removal of vegetation or the temporary removal of top soil.

Ecosystem: Living and nonliving elements in an environment, forming an interacting system inhabiting an identifiable space (adapted from Bedell 1998).

Ecosystem services: "The benefits people obtain from ecosystems. These include provisioning services such as food, water, timber, and fiber; regulating services that affect climate, floods, disease, wastes, and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling" (MEA 2005).

Ecosystem health: The "degree to which the integrity of the soil and the ecological processes of . . . ecosystems are sustained" (NRC 1994). An ecosystem may be called healthy if it is sustainable, remaining organized through time and resilient to stresses (Rapport et al. 1998).

Historical range of variation: A method of judging whether measured changes are notable using an ecological perspective. Ecosystems are dynamic by nature. Past efforts to manage ecosystems as static entities, with any deviation from what is deemed "in balance" fought against, have not been successful. By looking at the historic range of variability in attributes of ecosystems, managers may compare metrics to these ranges, and judge if the observed responses are unusual (reviewed in Daigle and Dawson 1996).

Metric: A measurable indicator. Indicators are quantitatively measurable aspects of a system that serve as surrogates for the status of the key ecological attributes. Indicators as surrogates are necessary because ecological attributes are not commonly directly measurable, and indicators can be selected specifically to be achievable.

Reclamation: To restore vegetation and landform of a site. Two levels of reclamation are used, interim and final. In interim reclamation, well operators restore vegetation and landform to the site, except for those areas needed to maintain production. Areas restored should be sufficient to maintain healthy, biologically active topsoil, control erosion, and minimize habitat and forage loss, visual impact, and weed infestation. After a well is plugged, final reclamation commences. The objective for reclamation is to set the course for eventual ecosystem restoration, including of the landform, vegetation community, hydrologic systems, visual resources, and wildlife habitats (USDI and USDA 2007).

Spatial Resolution: The area of earth a single pixel or cell in a remotely sensed image is intended to represent, such as 1 km x 1 km or 30 m x 30 m. Often resolution is identified by a single value with a square cell implied, such as 30-m resolution.

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